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Computational Optimization of a Natural Laminar Flow Experimental Wing Glove

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Computational optimization of a natural laminar flow experimental wing glove that is mounted on a business jet is presented and discussed. The process of designing a laminar flow wing glove starts with creating a two-dimensional optimized airfoil and then lofting it into a three-dimensional wing glove section. The airfoil design process does not consider the three dimensional flow effects such as cross flow due wing sweep as well as engine and body interference. Therefore, once an initial glove geometry is created from the airfoil, the three dimensional wing glove has to be optimized to ensure that the desired extent of laminar flow is maintained over the entire glove. TRANAIR, a non-linear full potential solver with a coupled boundary layer code was used as the main tool in the design and optimization process of the three-dimensional glove shape. The optimization process uses the Class-Shape-Transformation method to perturb the geometry with geometric constraints that allow for a 2-in clearance from the main wing. The three-dimensional glove shape was optimized with the objective of having a spanwise uniform pressure distribution that matches the optimized two-dimensional pressure distribution as closely as possible. Results show that with the appropriate inputs, the optimizer is able to match the two dimensional pressure distributions practically across the entire span of the wing glove. This allows for the experiment to have a much higher probability of having a large extent of natural laminar flow in flight.

I. Nomenclature

A	= Design variable array
B	= Array of binomial coefficients
C	= Class function
C_{local}	= Local chord length
C_p	= Pressure coefficient
C_{pt}	= Target pressure coefficient
Dx	= panel length
K	= Binomial coefficient
N1,N2	= Class function exponents
S	= Shape function
Δx	= x coordinate perturbation
Δz	= z coordinate perturbation
η	= y/c - non-dimensional spanwise length
Ψ	= x/c - Non-dimensionalized axial length

Acronyms

2D	= Two-dimensional
2.5D	= Two-dimensional transformed using sweep angle
3D	= Three-dimensional
CFD	= Computational fluid dynamics
CST	= Class-Shape-Transformation
LE	= Leading edge
TE	= Trailing edge

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NLF = Natural laminar flow

II. Introduction

NASA Dryden Flight Research Center does a significant amount of work testing new technologies to benefit aviation. One current project at Dryden uses a business jet as a test bed for flight testing experiments and raising their technology readiness levels. One of the current major experiments is a high Reynolds Number, natural laminar flow (NLF) airfoil that will be flight tested in the form of a wing glove. The wing glove will be placed on the left wing of the aircraft and will be approximately six feet in span. The glove is being designed in two main stages: two-dimensional (2D) airfoil design, and three-dimensional (3D) design and optimization. The 2D airfoil design is performed by Texas A&M University. The 2D design process starts by first developing an optimized pressure distribution for the highest extent of laminar flow at a certain flight condition. Two airfoils are generated for both the inboard and outboard sections of the glove using the optimized pressure distribution. Once the airfoils are created, the glove section is created by linearly lofting between the two airfoils. The glove section is then faired back into the wing of the aircraft using inboard, outboard and aft blends. This initial 2D glove design does not have the same chord-wise extent of laminar flow as the airfoils because the 3D flow properties such as swept wing cross flow and engine effects are not considered in the 2D design. To account for these factors, and to bring the extent of laminar flow back up to that seen in 2D, the 3D glove shape needs to be optimized. The process and the results of the 3D glove optimization is the main focus of this paper.

TRANAIR¹, a non-linear full potential code directly coupled with a boundary layer model, is used as the main tool in the optimization process. TRANAIR has a robust design optimization feature that allows constrained multi-point design that has been used on several Boeing aircraft. TRANAIR allows user-defined movement, constraint and objective functions including inequality constraints². The user-defined movement routine used is the Class-Shape-Transformation (CST) routine invented by Kulfan^{3,4}, which allows for fewer design variables than a traditional mesh point optimization. There is an active two inch clearance constraint that is imposed on the design so that the wing glove has 2" of room between the wing surface and the glove surface for the mounting devices. The objective function uses least-squares pressure coefficient (C_p) matching at three different span locations of the glove test section; inboard, outboard, and center. The target pressure distribution is the optimized 2D pressure distribution that has been transformed into 3D coordinates by the cosine of the sweep angle, and is used for all span stations. Optimization is inherently a learning and an iterative process, so choosing the constraints, objectives, and design variables is an ongoing process. The different methods attempted and the results of the optimization process are presented and discussed for a better understanding of the glove design and optimization.

III. Geometry and Grid Topology

A. Geometry

The aircraft that the wing glove is mounted on is a low-wing business jet, with aft body mounted engines, and a T-tail. The glove, seen in Figure 1, is placed on the left wing starting at approximately the 45% half span location and extends six feet outboard.

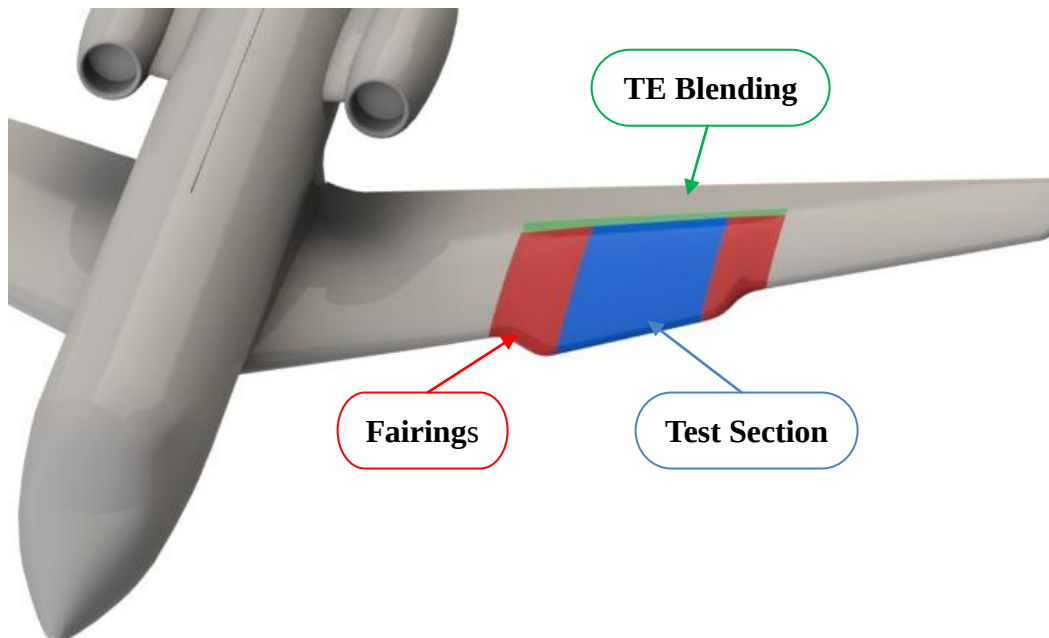


Figure 1. Glove mounted on the left wing. Blue-Test Section, Red-Fairings, Green-TE Blending.

The blue piece is the main test section, the red are the fairings that help smooth the cross flow over the wing to provide a clean test section surface, and the green part is the blending region. The glove test section has an inboard fairing that is 3.2 feet in span and an outboard fairing 2.5 feet in span. The glove blends back into the 60% chord location of the wing with a smooth tangency and curvature controlled blend. The glove geometry is offset from the wing with two inches of clearance, and protrudes from the leading edge of the wing by 2.3 feet.

Initial results for the 3D glove optimization are computed using only the wing and the glove to reduce the computational time. The final configuration used for the optimization included the wing with the mounted glove, the body and the engine. The T-tail was not included because it has an insignificant effect on the flow over the wing glove.

B. Grid Topology

The 3D optimization process starts with a full-aircraft TRANAIR simulation. TRANAIR uses a fully structured grid to discretize the surface geometry with a combination of point matching and linear abutments. The surface grid is created for the wing only geometry, as well as the wing/body/engine configuration seen in Figure 2. The wing only grid is created with the same parameters as the wing grid for the wing/body/engine configuration. Even though the glove is placed only on the port wing on the actual flight experiment aircraft, a symmetry plane was used for both configurations to reduce computational time. Since a symmetry plane is used, the aircraft grid is mirrored to the right hand side in order to better integrate with the TRANAIR solver.

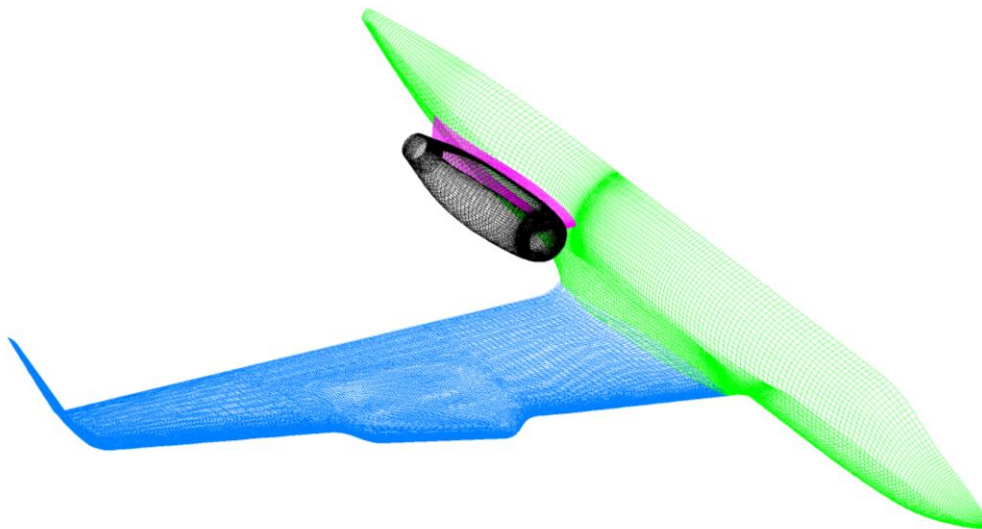


Figure 2. Fully structured surface grid; wing/glove–blue, body–green, pylon–magenta, engine–black

The volume grid for each solution is automatically generated by TRANAIR and adapted to refine flow features. The final volume grid is obtained by a sequence of successively refined grids that are adapted based on errors in the velocity gradients, and user inputs⁵. This allows the Cartesian grid to adapt to non-linear flow-features such as suction peaks and oblique shocks.

IV. Optimization Description

The optimization process uses TRANAIR for the flow solver and optimization package, with user-defined inputs for the geometry perturbation, constraint, and objective functions.

A. TRANAIR Optimization

TRANAIR has the capability to solve constrained aerodynamic design problem through the use of transpiration to approximate the surface movement. In the TRANAIR design process, the aerodynamic analysis problem on each grid is solved first and then the flow sensitivities are generated with respect to the design variables. An optimization problem is then constructed based on user inputs of the design variables, constraints and objectives. Constraints and objectives can either be flow or geometry based and are linearized with respect to the design variables. The constructed optimization problem is then sent through an optimizer which determines the values of the design variables that minimize the objective function. The geometry is perturbed through transpiration using the user-defined movement routine. The updated geometry and design variables are then used in the adaptive grid refinement process in preparation of solving the flow on the next grid⁵.

B. CST Design Method

The Class-Shape-Transformation routine from Kulfan^{3,4} is used to provide a mathematical description of a geometry through a generalized class function definition, with a series of shape functions to further define the geometry. The class

function is a generalized equation that allows for the creation of a wide variety of geometries. The shape function is a simple analytic function that controls the design parameters with only a few scalable values. The CST method is very powerful in its ability to model both 2D and 3D shapes efficiently with as few design variables as possible. In the optimization of the wing glove, the CST method was implemented as a perturbation routine.

The general form of the CST method is based on Bezier curves with an added class function which takes the general form seen in Eq. 1⁶

$$\zeta i(\psi) = C_{N2}^{N1}(\psi) \cdot S_i(\psi) \quad (1)$$

where C and S represent the class and shape functions respectively. Ψ equals the non-dimensionalized x coordinates (x/c). The class function is defined in Eq. 2⁶

$$C_{N2}^{N1}(\psi) = \psi^{N1} \cdot (1 - \psi)^{N2} \quad (2)$$

where exponents N1 and N2 define a variety of basic general classes of geometries. For classic NACA rounded nose and pointed end geometry, the N1 and N2 factors are 0.5 and 1.0 respectively. Since this paper focuses on a wing glove, the factors of 0.5 and 1.0 will be used throughout the design process. The shape function modifies the profile obtained by the class function and is represented by a Bernstein polynomial as shown in Eq. 3⁶

$$S_i(\psi) = K_i^N \cdot \psi^i \cdot (1 - \psi)^{N-i} \quad (3)$$

where N is the order of the Bernstein polynomial and K is the binomial coefficient which is defined in Eq. 4 as

$$K_i^N = \frac{N!}{i!(N-i)!} \quad (4)$$

The class and shape functions are then superimposed to produce a 2D CST curve seen in Eq. 5⁶

$$\zeta(\psi) = \sum_{i=0}^N A_i \cdot \zeta i(\psi) \quad (5)$$

A is the array of design variables that are defined through the optimization process. To expand the CST method to a 3D geometry, the shape functions now takes the form in Eq. 6⁶

$$S_i(\psi, \eta) = B_{i,j} \cdot Sx_i(\psi) \cdot Sy_j(\eta) \quad (6)$$

Where $\eta = y/c$ is the non-dimensional spanwise length and Sy is the shape function in the spanwise direction. The surface of the wing is now defined by Eq. 7⁶

$$\zeta(\psi, \eta) = \sum_{j=0}^{Ny} \sum_{i=0}^{Nx} A_{i,j} \cdot C_{1.0}^{0.5} \cdot S_i(\psi, \eta) \quad (7)$$

In the design problem, the wing X and Z coordinates are perturbed as seen in Eq. 8a and 8b

$$\Delta x = \frac{x}{c} * \zeta(\psi, \eta) * C_{local} \quad (8a)$$

$$\Delta z = \frac{z}{c} * \zeta(\psi, \eta) * C_{local} \quad (8b)$$

This CST method is the main perturbation routine used in the optimization process. In addition to the CST method, the glove is allowed to twist linearly from the inboard to outboard portions of the glove about the quarter chord. The perturbation routine also allows for the length in the streamwise direction to change. The length change is just a simple scaling of the X coordinates to shrink or grow the glove.

The original design of the glove has it blending back in continuously with the wing through the creation of the inboard and outboard fairings, and the aft blending regions. To maintain the continuity, the fairings and blending regions do not move where they intersect the wing surface, but they are allowed to be perturbed fully where they intersect the main test section of the glove. The amount they are allowed to be perturbed between the edges of the fairings is varied bi-cubically. This allows for the fairings and blending regions to maintain a nice smooth blend from the wing surface into the glove test section, while allowing them to be partially optimized.

C. Constraint and Objective Functions

The objective function for the optimization process is a common pressure matching routine. The 2D airfoil is designed with an optimized pressure distribution that has a favorable pressure gradient and other beneficial properties in order to maintain laminar flow. This pressure distribution is transformed into 3D coordinates by multiplying the 2D coordinates by the cosine of the sweep angle of the wing and scaling it to the correct size. This new pressure distribution will be referred to as the 2.5D C_p distribution. The 2.5D C_p is used as the objective function at three different span stations on the test section; inboard, outboard and center span. The objective function is written as a panel area weighted least squares fit seen in Eq. 9

$$Obj = Abs\left(\frac{Dx}{10}\right) * (C_p - C_{pt})^2 \quad (9)$$

Where Dx is the panel length in the X direction, C_p is the computed pressure coefficient at the node, and C_{pt} is the target pressure coefficient at the node. This equation is applied at every node on the given wing slice (inboard, outboard or center) and summed up to create one objective function value per wing slice.

The constraint function is a simple algorithm that ensures that the 2" clearance from the wing is maintained where necessary, and a 0" constraint is maintained everywhere else for the glove. The 2" clearance on parts of the glove is necessary to leave room for the mounting system. The 0" clearance is necessary everywhere else because the glove cannot physically protrude into the wing. Initially each node was an individual constraint with either a 2" clearance or 0" clearance constraint. This produced a total of around 14,000 individual constraints which increased the solution time significantly (from 8 to 50+ hours). Currently, only 4 nodes on each span slice are used as constraints for a total of 272 constraints. The 4 nodes are spread out over each airfoil section to ensure the necessary clearances are maintained everywhere.

V. 3D Optimization Results and Discussions

Any optimization problem is a learning process where the user sets up and runs an optimization, and then he makes a learned decision to change the objectives, constraints and design variables. This cycle is repeated as many times as needed to develop the best optimization setup for the specific problem. The results presented will be a reflection of the learning process and will help the reader understand the work and the effects of different approaches to the problem.

A. Wing Only Results

To start the optimization process, a design run is completed without any geometry constraints to see how the wing glove wants to move when there are no restrictions imposed upon it. Additionally, there is no length change allowed in the initial design routine. 12th order Bernstein polynomials are used for both the upper and lower surfaces for the CST method. The resulting glove from the initial optimization decreased the height of the upper surface in order to reduce the pressure peak on the aft region of the glove. A comparison between the original glove and the initially optimized glove is made using the center span section of the wing glove in Figure 3. Even though the entire wing glove and fairings were allowed to move, all of the comparisons of the geometry in the paper will be made using the center span location for easier visualization of the changes.



Figure 3. Comparison of the original and first optimized wing glove using the center span section. (Original – Green, Modified – Red)

The resulting pressure distributions on three of the span sections of the test section, along with the un-optimized glove pressure distributions are compared to the target C_p in Figure 4.

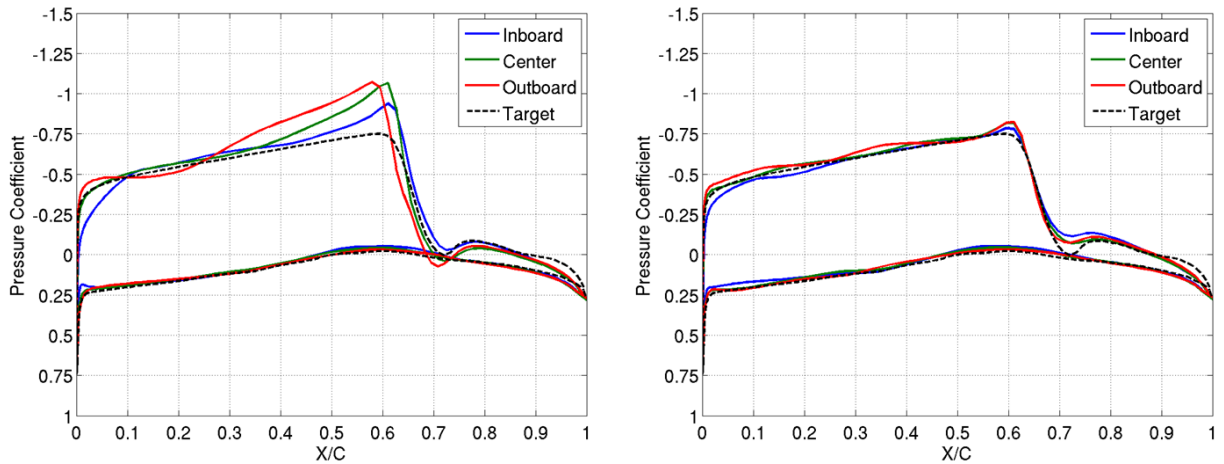


Figure 4. Pressure distributions across three sections wing glove. Left – Un-optimized glove, Right – First optimized glove.

The pressure distributions across the un-optimized glove are not at all uniform in the span direction. Flow near the leading edge (LE) of the wing glove on the outboard and inboard sections does not behave at all like the target pressure distribution. Additionally, there is a very large pressure peak near 60% chord across the entire glove which creates a large disturbance in the flow and reduces the extent of laminar flow seen over the wing glove. The large differences between the actual pressure distributions and the target validate the need to optimize the glove shape in 3D to increase the laminar flow capability.

Compared to the initial un-optimized glove design, the modified glove has much better pressure characteristics that are closer in shape to the target 2.5D C_p . Even though it is closer, it appears that the optimizer weights the aft sections of the upper surface much more than the LE section because of the panel area weighting in the objective function. It is very important to have a good pressure distribution on the upper surface, but for laminar flow, the LE is very critical. The major problem with this first optimization run is that the upper surface of the glove has less than 2" of clearance to the wing surface because no geometry constraints are added.

For the next design run, the panel area weighting was reduced in an effort to reduce the error of the pressure matching near the LE, and the length of the glove is allowed to be varied. The resulting center span of the wing glove is seen in

Figure 5 and the resulting pressure distributions on three of the span sections are shown in Figure 6.



Figure 5. Comparison of the original and second optimized wing glove using the center span section. (Original – Green, Modified – Red)

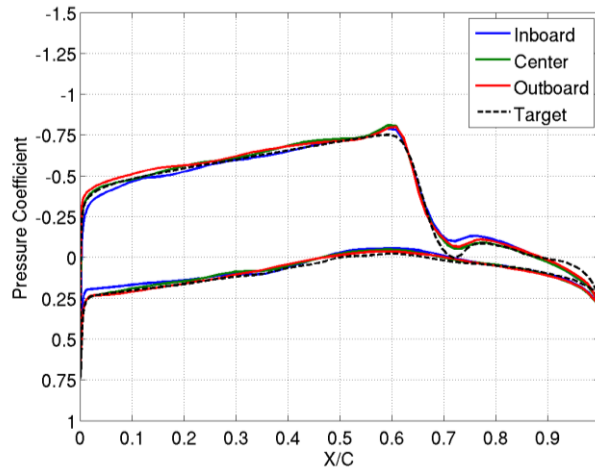


Figure 6. Pressure distributions across three sections of the second optimized wing glove.

Reducing the panel area weighting and allowing the wing glove to shrink in length shows a slightly better pressure matching to the target distribution. However, the 2” clearance constraint is still not satisfied, which now has to be included in the optimization.

With the clearance constraints added into the optimization problem, the resulting optimized glove leaves the required amount of room for the mounts and does not cross into the surface of the wing. The resulting glove shape and pressure distributions can be seen in Figure 7 and Figure 8 respectively.

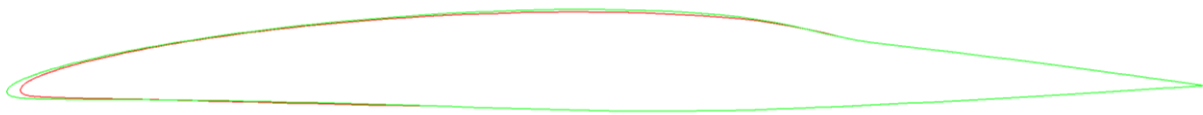


Figure 7. Comparison of the original and third optimized wing glove at the center span section. (Original – Green, Modified – Red)

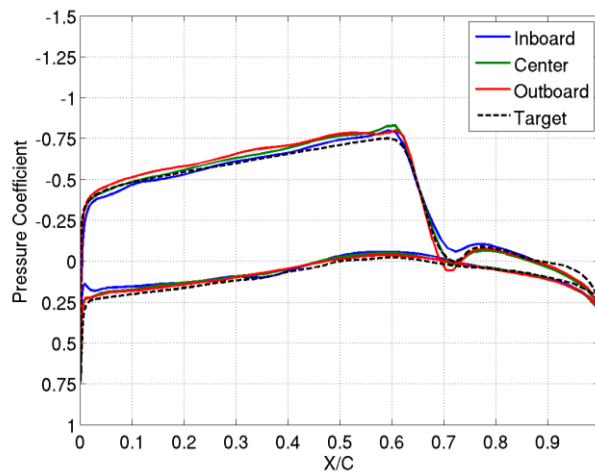


Figure 8. Pressure distributions across three sections of the third optimized wing glove.

The shape of the optimized geometry does not change significantly from the optimized geometry with no clearance constraints. With the constraints added, instead of reducing the thickness of the upper surface, the optimizer added twist to the wing glove, and also reduced the angle of attack at which it flew. This allowed for the clearance constraints to be satisfied while maintaining a close match to the target pressure distribution.

The pressure distributions from the third optimization are very close to a finely optimized glove. However, there is some waviness produced by the perturbation routine that needs to be smoothed out before the design is considered to be complete. Some methods of reducing this waviness have been to try and increase the order of the polynomials in the CST method to 24. Additionally, Kulfan developed a modification to the CST method by adding one extra term that increases the accuracy of the CST method for highly cambered LE airfoils and wings⁶. The addition of the term tends to make the CST representation of a given shape appear to have a higher order. The resulting pressure distributions for both attempts are shown in Figure 9.

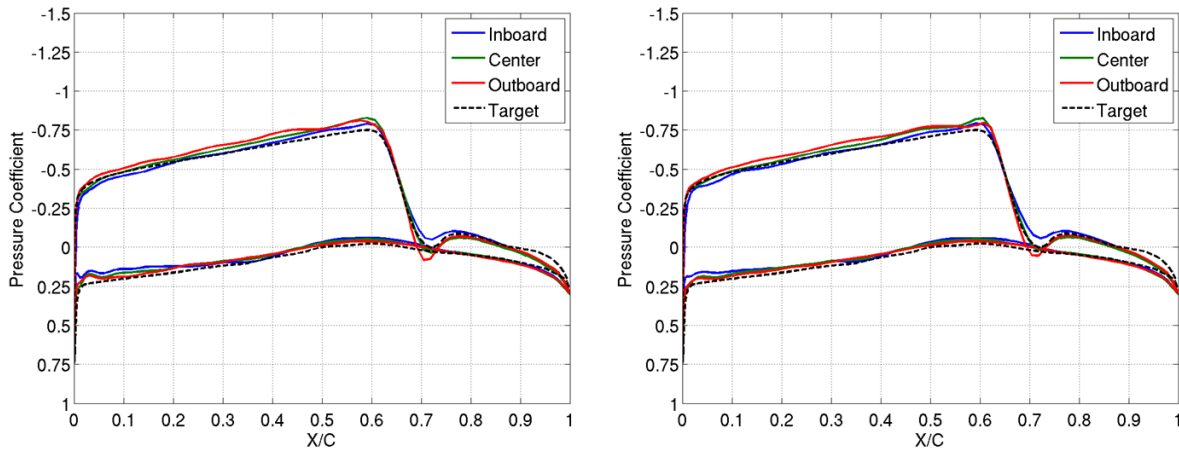


Figure 9. Pressure distributions across three sections of the fourth (left) and fifth (right) optimized wing gloves.

The increase in CST order from 12 to 24 does not have a large effect on the solution. Both gloves show waviness on the upper and lower surface, just with slightly different wavelengths. The LE modification reduced the small pressure peak near the lower surface LE, but it still does not reduce the waviness in the solution.

B. Wing/Body/Engine Results

All of the results previously shown have been computed on a model consisting of only a wing on a symmetry plane. The body and the engine are added in order to capture the interference effects and also the engine influence over the wing glove. Currently, only one optimization problem is run to determine how different the solution will be with the full configuration. The properties of the 3rd try at the optimization (12th order, constrained solution) were used for the wing/body/engine configuration which produced the pressure distributions in Figure 10.

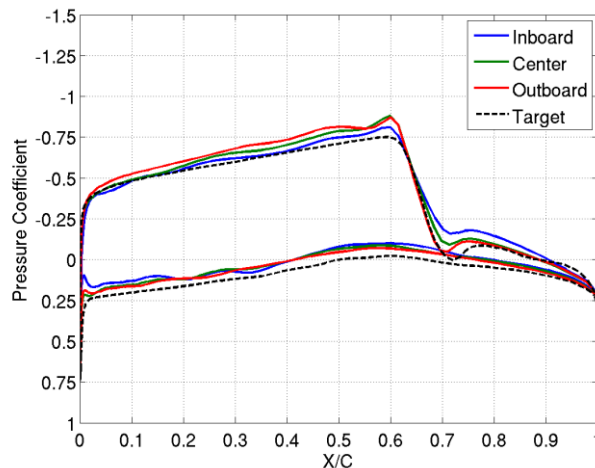


Figure 10. Pressure distributions across three sections of the first optimized wing glove with the engine and body included.

The resulting pressure distributions from the optimization look similar to those without the engine and body. The major

difference is the pressure side is offset from the target C_p distribution. Once the waviness issue is resolved on the wing only case, a few more computations will be performed with the full configuration in order to produce the final optimized wing glove.

VI. Future Work/Conclusions

The initial analysis from the 3D optimization shows very promising results. The results show that the glove target pressure distribution is attainable with small changes in the shape of the wing glove. Currently, the biggest problem with the optimization process is the resulting waviness from the geometry perturbation routine. A few different methods will be tried in an effort to reduce the waviness. First, the CST method will be re-formulated and tweaked with different orders of magnitudes and representations of the wing glove. If that is not sufficient, a grid smoothing routine will be attempted in order to smooth out the waviness. There is a concern however that the waviness is too large a wavelength to be properly fixed by a smoothing algorithm. If none of these attempts succeed, other geometry perturbation routines will be looked into including but not limited to, mesh point perturbation, b-splines, and others.

Further work will be done using the wing/body/engine configuration to produce the final optimized glove design. This optimized glove design will be as smooth as possible while matching the pressure distribution over as much of the span as possible. The new glove will be analyzed to determine the extent of laminar flow that it can support at the current flight test condition. When the glove is constructed and flown, pressure data, Infrared temperature maps and hotfilm data will be used to assess the extent of laminar flow over the glove and validate the CFD tools used to design and analyze the wing glove.

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